THE IDENTIFICATION OF THE SUBMILLIMETER GALAXY SMM J00266+1708

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ABSTRACT

We report the detection of 1.3 mm continuum and near-infrared $K-$band (2.2μm) emission from the submillimeter galaxy SMM J00266+1708. Although this galaxy is among the brightest sub-mm sources detected in the blank-sky surveys ($L \sim 10^{13} L_{\odot}$), SMM J00266+1708 had no previously known optical/near-infrared counter-part. We used sensitive interferometric 1.3 mm observations with the Owens Valley Millimeter Array to accurately determine the position of the sub-mm galaxy. Follow-up near-infrared imaging with the Keck I telescope uncovered a new faint red galaxy at $K = 22.5$ mag which is spatially coincident with the 1.3 mm emission. This is currently the faintest confirmed counter-part of a sub-mm galaxy. Although the redshift of SMM J00266+1708 is still unknown, its high sub-mm/radio spectral index suggests that the system is at high redshift ($z \gtrsim 2$). Approximately 50% or more of the sub-mm galaxies are faint/red galaxies similar to that of SMM J00266+1708. These ultraluminous obscured galaxies account for a significant fraction of the total amount of star-formation at high redshift despite being missed by optical/ultraviolet surveys.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: individual (SMM J00266+1708) — galaxies: starburst

1. INTRODUCTION

Deep surveys of the submillimeter sky using the Submillimeter Common User Bolometer Array (SCUBA) camera (Holland et al. 1999) on the James Clerk Maxwell Telescope have uncovered a population of ultraluminous dusty galaxies at high-redshift (Smail, Ivison, & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1998; Blain et al. 1999a). This population accounts for a large fraction of the extragalactic background at mm/sub-mm wavelengths (Blain et al. 1999b) and hence is important to our understanding of the distant universe. The sub-mm population is thought to contribute significantly to both the total amount of star-formation (Blain et al. 1999b) and AGN activity (Almaini et al. 1999) at high-redshift. The sub-mm population will likely show a mixture of AGN and starburst properties given their apparent similarities to the local population of ultraluminous ($L > 10^{12} L_{\odot}$) infrared galaxies (ULIGs). However, we could expect the majority ($\sim$ 70–80%) of the sub-mm galaxies to be predominantly powered by starbursts since this has been found for the local ULIGs (Genzel et al. 1998). The early CO and X-ray data on the sub-mm population support the starburst nature of the population by showing the presence of sufficient molecular gas to fuel the star-formation activity (Frayer et al. 1998, 1999) and the lack of expected X-ray emission if mostly dominated by AGN (Fabian et al. 2000; Hornschemeier et al. 2000). Observations of the dust-rich sub-mm galaxies complement the studies of the ultraviolet-bright Lyman-break sources (Steidel et al. 1996, 1999) which tend to be much less luminous at infrared wavelengths (Chapman et al. 2000). Only by studying both the Lyman-break and the sub-mm populations of galaxies will a complete picture for the star-formation history of the universe emerge.

In order to understand the nature of the sub-mm population, we have been carrying out multi-wavelength observations of individual systems in the SCUBA Cluster Lens Survey (Smail et al. 1998). This survey represents sensitive sub-mm mapping of seven massive, lensing clusters which uncovered 15 background sub-mm sources. The advantage of this sample is that the amplification of the background sources allows for deeper source frame observations. Also, lensing by cluster potentials does not suffer from differential lensing so that the observed flux ratios will represent intrinsic values, despite the possible variation of source size at different wavelengths.

The most challenging aspect for follow-up studies of the sub-mm population is determining the proper counter-parts to the sub-mm emission and obtaining their redshifts (Ivison et al. 1998, 2000a). The large 15″ SCUBA beam leaves ambiguity in identifying the galaxy associated with the sub-mm emission. The early results based on optical imaging and spectroscopy were overly optimistic in the identification of the sub-mm counter-parts (Smail et al. 1998; Barger et al. 1999; Lilly et al. 1999). Radio data (Smail et al. 2000a) and initial near-infrared (NIR) imaging (Smail et al. 1999) suggest that several of the original candidate optical counter-parts (e.g., Barger et al. 1999) are incorrect. Despite their ultra-high luminosities, many sub-mm galaxies are nearly completely obscured by dust at ultraviolet/optical wavelengths. For these highly obscured galaxies, follow-up radio (Smail et al. 2000a) and/or mm interferometry (Downes et al. 1999) as well as near-infrared observations are required in order to uncover the proper counter-part. The galaxy SMM J00266+1708 is an excellent example of such a source.

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2. OBSERVATIONS

2.1. *Background Data on SMM J00266+1708*

The sub-mm galaxy SMM J00266+1708 is the second brightest galaxy in the SCUBA Cluster Lens Survey (Smail et al. 1998). Initially, the source was tentatively associated with a possible interacting pair of galaxies, M1 and M2, revealed by deep I-band imaging ($3\sigma = 26.1$ mag) with the *Hubble Space Telescope* [*HST*] (Smail et al. 1998). Spectroscopy of the galaxy M2 showed a bright [O II] emission line at $z = 1.226$, consistent with a luminous star-forming galaxy (Barger et al. 1999). In the fall of 1998, we searched for redshifted CO(2→1) emission corresponding to the redshift of M2 at the Owens Valley Millimeter Array[4] (OVRO). We failed to detect any CO emission at the redshift of M2; $S(\mathrm{CO}) < 1.3\,\mathrm{Jy\,km\,s^{-1}}$ (3σ), assuming a standard $300\,\mathrm{km\,s^{-1}}$ line width. If M2 was the correct counter-part and the source was similar to the sub-mm galaxies with previous CO detections (Frayer et al. 1998, 1999), we would have expected a CO(2→1) line strength of approximately $7\,\mathrm{Jy\,km\,s^{-1}}$. The nondetection of CO questions the association of M2 with the sub-mm galaxy. Additional optical spectroscopy showed that M1 is at the redshift of the foreground cluster ($z = 0.39$), and hence, M1 and M2 are not an interacting pair after all (Barger et al. 1999). These results further bring into doubt the initial association of M1 and M2 with the sub-mm emission based on optical morphology alone.

Besides M1 and M2, the only other optically visible source spatially consistent with the SCUBA position is M8 (Fig. 1). However, the galaxy M8 shows no unusual properties that would suggest an association with a luminous sub-mm source. More significantly, the field has a weak radio source (Smail et al. 2000a) whose position is consistent with the SCUBA source, but is slightly offset from M8. Since the brightest sub-mm galaxies tend to have radio counter-parts (Smail et al. 2000a; Barger, Cowie, & Richards 2000), we could reasonably expect an association between the sub-mm galaxy and the radio source. If this is the case, the radio emission of SMM J00266+1708 is too weak to be consistent with a redshift of $z = 0.44$ for M8 (Barger et al. 1999), based on the redshift dependency predicted for the sub-mm/radio spectral index (Carilli & Yun 1999). Although the sub-mm/radio spectral index only provides an estimate of the redshift given the uncertainties of source temperature and properties (Blain 1999), it does provide a powerful technique for discriminating between low-redshift ($z \lesssim 0.5$) and high-redshift ($z \gtrsim 2$) galaxies. SMM J00266+1708 is expected to be at redshifts $z > 2$ since its sub-mm/radio spectral index of $\alpha = 1$ is much larger than any known galaxy at low redshift (Smail et al. 2000a). Therefore, M8 is not likely the sub-mm counter-part. Since none of the optically detected galaxies are plausibly associated with the sub-mm emission, we have carried out mm-continuum and near-infrared observations of SMM J00266+1708.

2.2. *OVRO 1.3 mm Continuum Observations*

We have taken sensitive 1.3 mm interferometric observations of SMM J00266+1708 in order to accurately constrain the position of the sub-mm source. SMM J00266+1708 was observed several times using the OVRO array in 1999. Approximately 10 hours of on source data were obtained during good conditions in the low resolution configurations of the array (baseline lengths ranging from 15m to 119m). We observed with four separate 1 GHz continuum bands centered at 229.0, 230.5, 233.5, and 235.0 GHz. The 4 GHz of total continuum bandwidth represents a factor of two increase in bandwidth over what was previously achievable at OVRO.

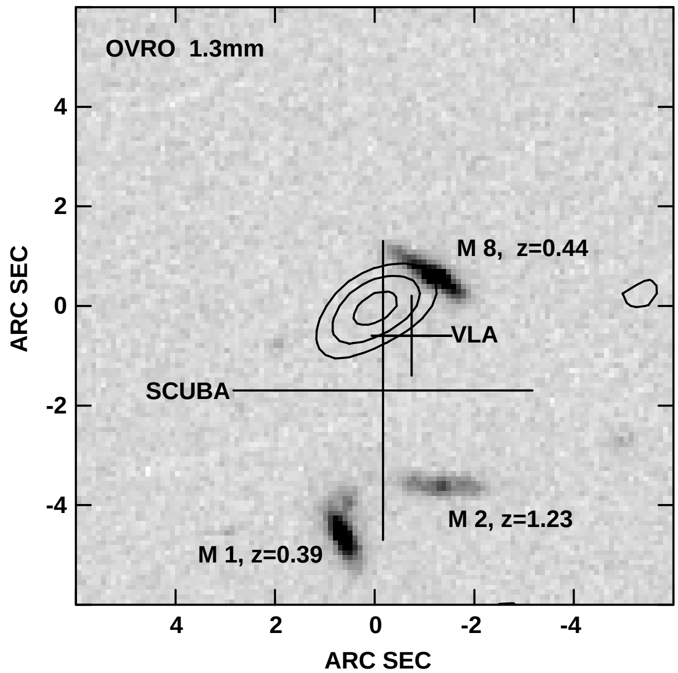

FIG. 1.— The OVRO 1.3 mm contour map overlaid on the *HST I*-band optical image (Smail et al. 1998). The rms level is 1.1 mJy/beam, and the contour levels are $1\sigma \times (-3, 3, 4, 5)$. The source is unresolved by the 2″ OVRO beam. The position of the 21 cm radio source (Smail et al. 2000a) is shown by the cross labeled "VLA", while the positional uncertainty of the sub-mm source is marked by the cross labeled "SCUBA".

We observed the bright quasar 3C454.3 every 20 minutes for amplitude and phase calibration. Since 3C454.3 is 22 degrees from SMM J00266+1708, we also interweaved observations of the nearby quasar 0007+106 (B1950.0) in order to test the quality of the calibration. The systematic positional uncertainty of the data is estimated to be better than 0.″3. Observations of the planets Uranus and Neptune were used to calibrate the absolute flux scale. By using the flux history of 3C454.3, we estimate a flux calibration uncertainty of 20% for the data.

We combined the data for the four individual 1 GHz bands to produce the 1.3 mm detection at a mean frequency of 232.0 GHz. The contours in Figure 1 show the resultant natural–weighted image. No primary beam correction was required since the source was located within 4″ (1/8 of the primary beam width) of the phase center. We made no correction for possible variations of source strength across the four individual bands. These varia-

[4]The Owens Valley Millimeter Array is a radio telescope facility operated by the California Institute of Technology and is supported by NSF grant AST 96–13717.

tions are expected to be less than 10%, assuming dust emission, and were undetected within the uncertainties of the data.

2.3. *Keck K-band Imaging*

After the 1.3 mm detection, we obtained K-band (2.2μm) data to search for the galaxy responsible for the sub-mm emission at the position derived from the OVRO data. We observed SMM J00266+1708 using the Near Infrared Camera (NIRC) on Keck I[5] on UT 1999 October 01. NIRC is a 256×256 pixel InSb detector with a pixel scale of $0\farcs15$ (Matthews & Soifer 1994). We observed using the standard K-band filter instead of the bluer K_s filter since the object is expected to be red. Integrations were taken using 10×6 second coadds, and we randomly dithered the integrations within a $8'' \times 8''$ box to provide uniformity across the image. We obtained a total of 4.3 hours of data on source. The seeing-disks of the stars observed throughout the night varied from $0\farcs3$ to $1''$ (FWHM).

In reducing the data, a combined set of dark frames was subtracted from each individual exposure to remove the dark current as well as the bias level. The dark-subtracted exposures were divided by a normalized skyflat which was generated from the on object exposures themselves. Frames were sky-subtracted using the temporally–adjacent images to produce the reduced exposures. The individual reduced exposures were aligned to the nearest pixel using common objects in the frames. We observed a set of near-infrared standard stars (Persson et al. 1998) at a range of airmasses in order to correct the data for extinction. The uncertainty of the derived magnitude scale is estimated to be better than 0.04 magnitude, based on the dispersion in the zero-points derived throughout the night.

3. RESULTS

3.1. *Images*

Figure 1 shows the 1.3 mm continuum map. The source was detected at the 5σ level and was unresolved with a synthesized beam size of $\theta_b = 2\farcs3 \times 1\farcs9$. At the observed frequency of 232 GHz (1.29 mm), we derive a flux density of 6.0 ± 1.1 mJy by fitting a Gaussian to the peak of the emission. The total uncertainty in the flux is 28% which includes the 20% calibration error and the rms error of 20% combined in quadrature. The strength of the 1.3 mm source is consistent with extrapolating the thermal dust spectrum expected from the sub-mm source (Fig. 3). We conclude that the 1.3 mm source is associated with the SCUBA source and is likely representative of the bulk of the sub-mm emission.

Figure 2 shows the K-band image. We detected a new galaxy $1\farcs5$ south-east of the nucleus of M8 at the position of the OVRO 1.3 mm continuum source. Since the seeing varied significantly throughout the night, we combined only the best 2.4 hours of data to produce the K-band image. After convolving the data with a 2 pixel (FWHM) Gaussian to reduce pixel-to-pixel variations, the resolution of data is $0\farcs5$ (FWHM), including seeing. The image has a 1σ limiting K-band surface brightness of $\mu = 24.8\,\mathrm{mag}/\Box''$ or 0.04μJy/beam, adopting 646 Jy for the flux density equivalent for a zero $K-$band magnitude (Neugebauer et al. 1987).

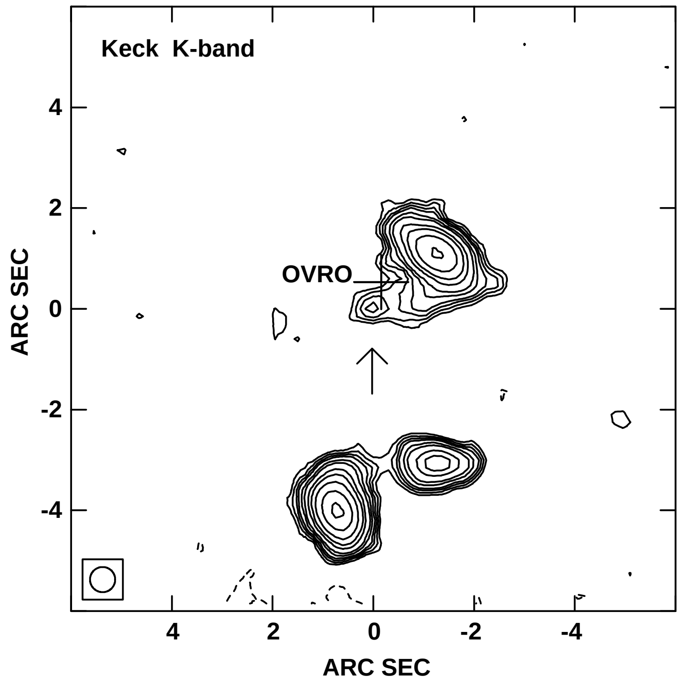

FIG. 2.— The Keck K-band (2.2μm) image. The arrow points to the new galaxy thought to be the counter-part of SMM J00266+1708. The rms of the image is 24.8 mag/$\Box''$ (0.04μJy/beam), and the contours are $1\sigma \times (-3, 3, 4, 5, 6, 8, 10, 15, 20, 30, 50, 80)$. The seeing disk (beam) of the NIR data is shown in the lower left ($0\farcs5 \times 0\farcs5$). The position of the 1.3 mm source is shown by the cross labeled "OVRO".

Photometry on the galaxy was done using an aperture to sum up the emission from the regions around the south-eastern peak that are well separated from M8. The integrated emission for the galaxy was detected at about the 10σ level with a magnitude of $K = 22.45 \pm 0.11$ ($0.68 \pm 0.07\,\mu$Jy, $K_{\rm AB} \simeq 24.3$). There is additional emission westward from the south-eastern peak and near M8. There is no evidence in the $I-$band image for this extension. If we assume that this emission is associated with the south-eastern peak, we would derive a total magnitude of $K = 21.52$ after subtracting the bright disk of M8 from the image. For the remainder of the paper, we neglect this additional emission since it is unclear what fraction is associated with M8, the south-eastern peak, or neither.

3.2. *Astrometry*

The K-band image was registered to the *HST* optical image on the APM coordinate system using the galaxies M1 and M8. The optical astrometry in the *HST* image has an rms uncertainty of only $0\farcs2$. However, the dominant source of registration error in comparing the K-band data with the radio and 1.3 mm data is due to the the systematic offsets between the APM system and the radio reference frame (Johnston et al. 1995). These offsets

[5]The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Keck Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

TABLE 1
OBSERVED PROPERTIES OF SMM J00266+1708

Wavelength	α(J2000) $00^{\rm h}26^{\rm m}$	δ(J2000) $+17°08'$	Flux[a]	Telescope
21.4 cm	$34^{\rm s}.06 \pm 0^{\rm s}.06$	$33''.1 \pm 0''.8$	$94 \pm 15\,\mu$Jy	VLA
3.54 cm	...	...	$< 34\,\mu$Jy(3σ)	VLA
1.29 mm	$34^{\rm s}.10 \pm 0^{\rm s}.04$	$33''.7 \pm 0''.5$	6.0 ± 1.7 mJy	OVRO[b]
850 μm	$34^{\rm s}.1 \pm 0^{\rm s}.2$	$32'' \pm 3''$	18.6 ± 2.4 mJy	JCMT
450 μm	...	...	< 60 mJy (3σ)	JCMT
2.2 μm	$34^{\rm s}.11 \pm 0^{\rm s}.07$	$33''.2 \pm 1''.0$	$0.68 \pm 0.07\,\mu$Jy ($K = 22.45 \pm 0.11$)	Keck[b]
0.8 μm	...	...	$< 0.09\,\mu$Jy (3σ) ($I < 26.1$)	HST

[a]Flux uncertainties include both systematic and rms errors.
[b]Observations presented in this paper.

may be as large as $1''$ which we adopt as a conservative estimate of the total error in the K-band position. The positional error for the 1.3 mm source is $0''.5$. This includes a systematic astrometry uncertainty of $0''.3$ from calibration combined in quadrature with the statistical error related to the signal–to–noise (S/N) of approximately $0''.4$ $(\theta_b/[S/N])$. The 21 cm radio data have a synthesize beam size of $5''$ and a positional error of about $0''.8$ $(\theta_b/[S/N])$. The 850μm source detected by SCUBA has a positional accuracy of approximately $3''$ (Smail et al. 1998).

The positions of SMM J00266+1708 measured at 1.4 GHz, 1.3 mm, 850μm, and 2.2μm are all consistent with each other within the errors (Table 1). The positional coincidence alone suggests an association between the sources at different wavelengths. The probability of randomly finding a 22.5 mag K-band galaxy within a 1 square-arcsec box is only 1%, based on the observed K-band surface densities of galaxies (Djorgovski et al. 1995; Moustakas et al. 1997). By taking into account the red nature of the galaxy $(I-K > 3.6)$, the likelihood of a random association decreases even more. Only about 10% of faint galaxies $(22.0 \leq K \leq 22.9)$ have $(I-K) > 3.5$ (Moustakas et al. 1997). Hence, the probability of a chance association of such a faint red galaxy with the 1.3 mm source is only 10^{-3}. An even stronger case can be made on the association between the radio source and the 1.3 mm source. Radio source counts (Richards et al. 1999; Richards 2000) imply the probability of randomly finding such a strong radio source within 1 square arcsec of the 1.3 mm source is only about 10^{-5}. We conclude the sources detected at 1.4 GHz, 1.3 mm, 850μm, and 2.2μm are all likely associated with each other.

3.3. *Spectral Energy Distribution and Redshift*

Table 1 presents the flux density measurements and upper-limits observed for SMM J00266+1708. The 21 cm radio data are presented by Smail et al. (2000a). We measure a flux density of $94 \pm 15\,\mu$Jy for the 21 cm radio source by fitting a Gaussian to the unresolved emission. We also report a 3.5 cm upper-limit for the galaxy based on sensitive observations of the cluster (A. R. Cooray, private communication). The sub-mm flux at 850μm has been previously tabulated by Barger et al. (1999), and the 450μm upper limit is discussed by Smail et al. (2000b). The optical I-band limit of 26.1 mag is derived from the observations presented by Smail et al. (1998). The 1.3 mm and K-band measurements are based on the observations presented in this paper.

As stated earlier (§2.1), SMM J00266+1708 is thought to lie at a high redshift of $z \gtrsim 2$ based on the sub-mm/radio spectral index of the galaxy (Smail et al. 2000a). High redshifts are also required to account for the low 450μm/850μm ratio, assuming dust emission with properties similar to that found in low-redshift luminous starbursts (Dunne et al. 2000). The optical and NIR imaging data by themselves provide little constraint on the redshift of SMM J00266+1708 given the wide range of optical/NIR properties found for the sub-mm population (e.g., Ivison et al. 2000a). The best redshift constraints for SMM J00266+1708 come by fitting the spectral energy distribution (SED) of the galaxy from radio to sub-mm wavelengths. Figure 3 shows the observed SEDs of the low redshift ULIGs Arp 220 and Mrk 231 (Rigopoulou, Lawrence, & Rowan-Robinson 1996), as well as the $z = 1.44$ extremely red galaxy (ERO) HR10 (Dey et al. 1999), the relatively blue sub-mm starburst SMM J14011+0252 (Ivison et al. 2000a), and the sub-mm galaxy SMM J02399-0136 which contains an AGN (Ivison et al. 1998). These ULIG systems are chosen for comparison since they represent the reasonable range of possible SEDs expected for the sub-mm population. Assuming a likely range of dust temperatures (30–50 K) and fitting all the data to the nearest 0.5 redshift unit, we estimate a redshift of $z = 3.5 \pm 1.5$ for SMM J00266+1708.

The wide range of optical flux densities and colors for ULIGs/sub-mm galaxies (Fig. 3) demonstrates the difficulty of attempting to estimate the far-infrared luminosities of ultraluminous galaxies based solely on optical observations (e.g., Adelberger & Steidel 2000). Bolometric luminosities estimated from sub-mm flux densities are significantly more robust since the observed emission from high-redshift galaxies arises near the peak of the SED (Hughes, Dunlop, & Rawlings 1997).

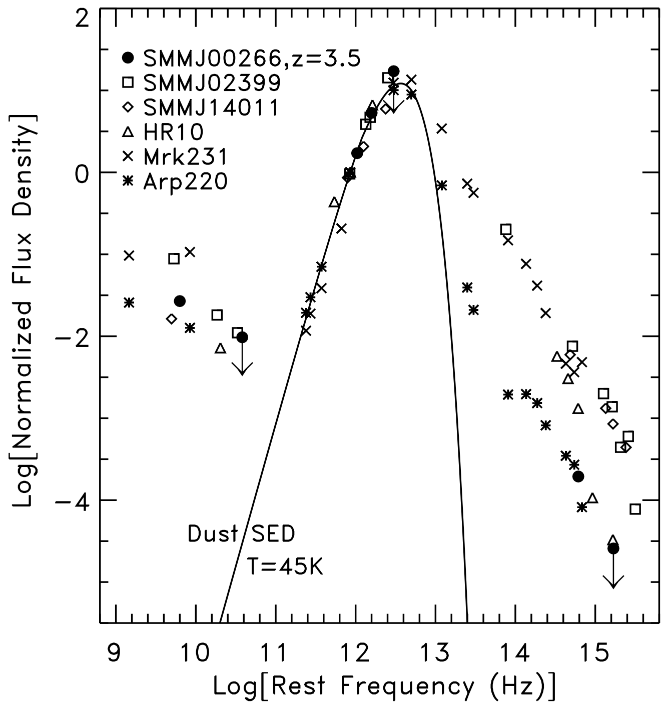

FIG. 3.— The SED of SMM J00266+1708 (solid circles) adopting the best fit redshift of $z = 3.5 \pm 1.5$ compared to other ULIG systems. All data have been normalized to a rest wavelength of 350μm. The upper-limits for SMM J00266+1708 are marked with downward arrows. The solid line shows an example SED from dust emission assuming a typical temperature of $T = 45$ K and $\beta = 1.5$ for the power-law dependence of the dust absorption coefficient.

3.4. *Lensing*

In this section, we estimate the effect of gravitational lensing. SMM J00266+1708 is amplified by the potential of the $z = 0.39$ foreground cluster Cl 0024+16. Assuming a redshift of $z = 1.23$, Barger et al. (1999) find an amplification factor of 1.6 due to the cluster. Adopting a more realistic source redshift of $z \sim 3.5$, the amplification factor is increased to approximately 2.1 using the relationships given by Schneider, Ehlers, & Falco (1992) to rescale the appropriate angular size distances. For the adopted cosmology ($H_o = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_o = 0.5$), the expected amplification factor due to the cluster is fairly insensitive to redshift for $z \gtrsim 2$.

Since SMM J00266+1708 is near the line of sight of the galaxy M8 ($z = 0.44$), we could expect additional gravitational lensing due to M8. To estimate this effect, we approximate both M8 and SMM J00266+1708 as point sources and use the equations for a simple Schwarzschild lens (Schneider et al. 1992). M8 appears to be a normal spiral galaxy with a typical absolute V-band magnitude of $M_V = -20$ (Smail et al. 1997). Assuming a total mass of $2 \times 10^{11} M_\odot$ within the central 10 kpc of M8 (which corresponds to the angular separation of 1.″5 between SMM J00266+1708 and M8), we estimate that SMM J00266+1708 is amplified by a factor of 1.14 due to M8. Hence, we expect a total magnification factor of about 2.4 for SMM J00266+1708, including lensing by both the cluster and M8. The total amplification factor is sensitive to the mass of M8 and the cluster model and could realistically be between approximately 2–4.

SMM J00266+1708 is the second sub-mm galaxy (ERO-N4 is the other example [Smail et al. 1999]) found in the Cluster Lens Survey thought to be lensed by a low redshift spiral galaxy. These results may suggest that lensing due to galaxies could play a significant role on the sub-mm population as a whole (e.g., Downes et al. 1999). The current observations are consistent with predictions and imply that future mm/sub-mm surveys covering large areas of the sky should detect several strongly lensed sources (Blain, Möller, & Maller 1999).

4. DISCUSSION

We have concentrated our follow-up studies on the nine brightest galaxies detected in the sub-mm Cluster Lens Survey (Smail et al. 1998). Currently, only three of the nine galaxies have optical counter-parts with redshifts. Two of these have been confirmed by CO observations at OVRO (Frayer et al. 1998, 1999), and the third is a Sy 1.5 ring galaxy at $z = 1.06$ recently detected in CO with the IRAM interferometer (Kneib et al. 2000).

At least four of the nine systems are undetected at optical wavelengths ($I > 26$–27 after correcting for lens amplification) and have only been detected with K-band imaging. Two of these are bright enough ($K = 19.1$, 19.6 mag) to be classified as EROs (Smail et at. 1999). An additional faint $K = 21$ galaxy was found associated with a relatively bright (500 μJy) radio counter-part (Ivison et al. 2000a). SMM J00266+1708 is the faintest sub-mm counter-part found to date at $K = 22.5$. Only two of the nine sources still require deep K-band imaging and have uncertain counter-parts. Depending on the results for these last two unknown systems, the data suggest that approximately 40%–70% (4/9–6/9) of the sub-mm population as a whole are very faint/red galaxies which are undetected at optical wavelengths. It is still unclear what fraction of the sub-mm galaxies are EROs [$R - K > 6$] (Thompson et al. 1999). At least two out of nine ($\gtrsim 20\%$) galaxies in the Cluster Lens Survey are EROs (Smail et al. 1999), and other sub-mm surveys have uncovered additional faint EROs associated with SCUBA sources (Ivison et al. 2000b). With much deeper optical observations of the faint sub-mm galaxies, we could realistically expect the source density of EROs to increase significantly.

4.1. *Intrinsic Properties of SMM J00266+1708*

In order to estimate the properties of SMM J00266+1708, we adopt a redshift of $z = 3.5$, a lensing magnification of 2.4, and a cosmology of $H_o = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_o = 0.5$. Given the redshift uncertainty, we cannot accurately determine many of the intrinsic properties of SMM J00266+1708. One exception is the far-infrared (FIR) luminosity which is relatively insensitive to redshift for $z \gtrsim 1$ (Blain & Longair 1993). From the 850μm measurement, the implied intrinsic FIR luminosity (Condon 1992) for SMM J00266+1708 is $L(\mathrm{FIR}) \sim 1 \times 10^{13} L_\odot$. This corresponds to a star-formation rate of massive stars ($M > 5 M_\odot$) of approximately 500–900 $M_\odot\,\mathrm{yr}^{-1}$ (Scoville et al. 1997; Condon 1992). Although this star-formation rate is much higher than that inferred for Lyman-break starbursts, these results are consistent with estimates for other sub-mm galaxies (Ivison et al. 1998, 2000a). It is still not known whether or not an AGN contributes significantly to the bolometric luminosity of SMM J00266+1708. If an AGN is present, it is not a strong radio source and must be heavily obscured at optical wavelengths (Fig. 3). Based on its SED, SMM J00266+1708 appears most similar to highly-reddened ULIG/starbursts such as Arp 220 or HR10 at a redshift of $z \sim 3.5$.

4.2. *Comparison of Sub-mm and Lyman-break Populations*

Most sub-mm galaxies are similar to SMM J00266+1708 in being too faint and/or too red to be included in the Lyman-break surveys (e.g., Steidel et al. 1999). The one notable exception is sub-mm selected galaxy SMM 14011+0252 (Ivison et al. 2000a), but this galaxy is much brighter in R-band than any of the optically-selected Lyman-break galaxies (Adelberger & Steidel 2000). Just as the sub-mm galaxies are generally excluded from Lyman-break surveys, the Lyman-break galaxies are excluded from the sub-mm surveys due to a lack of sensitivity (Chapman et al. 2000). Since there is very little overlap between the dust-rich sub-mm galaxies and the ultraviolet-bright Lyman-break systems, studies of both populations are complementary to our understanding of the distant universe.

The sub-mm galaxies are ultraluminous ($> 10^{12} L\odot$) systems, while the Lyman-break galaxies are about 10 times more common and at least 10 less luminous than the sub-mm systems (e.g., Lilly et al. 1999). Despite their different luminosities, it has been suggested that both populations could represent the formative phases of massive galaxies (Giavalisco et al. 1998; Blain et al. 1999c). In this scenario, the sub-mm systems may be associated with a very luminous, short-lived and heavily dust enshrouded starburst, while the Lyman-break galaxies would be associated with a longer-lived, less luminous phase of star formation (Blain et al. 1999c). Alternatively, the sub-mm and Lyman-break systems could represent two distinct populations of galaxies, e.g., ULIGs and sub-L^* galaxies respectively.

A direct method of discriminating between these two scenarios is by measuring the relative masses of the sub-mm and Lyman-break systems. The detection of massive reservoirs of molecular gas (Frayer et al. 1998, 1999), suggests that the sub-mm population is associated with gas-rich massive galaxies ($\gtrsim L^*$). The molecular gas masses of the sub-mm galaxies are 10–50 times greater than that found for the Milky Way. In contrast, the best studied Lyman-break galaxy cB58 (Yee et al. 1996; Pettini et al. 2000) has even less molecular gas than the Milky Way, after correcting the observed CO upper-limit for lensing and suspected metallicity effects (Frayer et al. 1997). Therefore, the Lyman-break galaxies may be sub-L^* systems representing the building blocks of more massive galaxies as suggested by Lowenthal et al. (1997). Clearly, detailed studies of a large number of sub-mm and Lyman-break systems must be completed before we could conclude whether or not the Lyman-break systems are as massive as the sub-mm galaxies.

4.3. *Star-Formation Contribution at High Redshift*

The importance of the sub-mm galaxies to the global star-formation rate at high-redshift is an active area of discussion (Hughes et al. 1998; Guiderdoni et al. 1998; Blain et al. 1999b, 1999c; Trentham et al. 1999; Peacock et al. 2000). Based on the observed sub-mm counts (Blain et al. 1999a), the ultraluminous sub-mm galaxies ($> 10^{12} L_\odot$; $S[850\mu\mathrm{m}] \gtrsim 1\,\mathrm{mJy}$) contribute approximately 50% of the extragalactic background (Blain et al. 1999b). Less than 30% of these ultraluminous sub-mm sources are expected to be dominated by AGN unless there is a large population of highly obscured AGN which is Compton-thick at X-ray wavelengths (Almaini et al. 1999; Gunn & Shanks 2000). These predictions are consistent with current observations of the sub-mm population (Ivison et al. 2000a) and the results found for ULIGs in the local universe (Genzel et al. 1998). Assuming 30% of the sub-mm galaxies are dominated by AGN implies that on order of 35% of the extragalactic background arises from star-formation in ultraluminous sub-mm galaxies. It is truly remarkable that such a high fraction of all star-formation at high-redshift occurs in ULIG/sub-mm galaxies. In contrast, ULIGs only contribute about 0.2% of the total amount of star formation in the local universe, based on the survey of Kim & Sanders (1998). Hence, the evolution in the amount of star formation occurring in ULIGs is about 100 times stronger than the global increase of the star-formation rate at high redshift seen for all galaxies (Madau et al. 1996; Steidel et al. 1999). This may suggest the increasing importance of merger-induced luminous starbursts at high redshifts (Blain et al. 1999c).

The results presented for SMM J00266+1708 have important implications on our general understanding of star-formation at high redshift. Roughly half of the total amount of star formation at high redshift is thought to occur in the sub-mm galaxies (Blain et al. 1999b), while the other half is inferred from the optically–selected Lyman-break sources (Peacock et al. 2000). Even for the Lyman-break galaxies, most of their star-formation (∼80%) is obscured by dust at observed optical wavelengths (Peacock et al. 2000; Adelberger & Steidel 2000). Therefore, re-radiated dust emission is a much better indicator of the star-formation activity than optical/ultraviolet light. Since about 50% of the sub-mm galaxies are undetected at optical wavelengths, a significant fraction (∼ 25%) of the total amount of high-redshift star formation may occur in the very faint/red sub-mm galaxies similar to SMM J00266+1708. Similar conclusions were also reached for a radio-selected sample of sub-mm galaxies with faint optical counter-parts (Barger et al. 2000). The fact that many of the most luminous high-redshift starbursts/AGN are too faint to be studied at optical wavelengths highlights the importance that future sensitive mm–NIR wavelength instruments will have on our understanding of the distant universe.

5. CONCLUDING REMARKS

We report the identification of the sub-mm source SMM J00266+1708 with a faint red galaxy ($K = 22.5$ mag) which is undetected at optical wavelengths. The current data for the sub-mm Cluster Lens Survey suggest that 40%–70% of the sub-mm population as a whole are undetected at optical wavelengths. These faint/red sub-mm galaxies are thought to contribute significantly to the total amount of star formation at high redshift and are hence important to our understanding of the early evolution of galaxies.

SMM J00266+1708 has an extremely high luminosity of approximately $10^{13}L_{\odot}$ even after correcting for lensing. The redshift of SMM J00266+1708 is currently unknown, but the galaxy is expected to be at a redshift $z > 2$. Obtaining a redshift will be extremely challenging with current instrumentation. At $K = 22.5$ mag, the galaxy pushes the capabilities of even the largest ground based telescopes. Since the galaxy is relatively red ($I-K > 3.6$), we expect Hα to be the brightest optical emission line, and perhaps the only optical line currently detectable based on comparisons with the ERO HR10 (Dey et al. 1999). If the redshift is similar to that estimated from the SED of the galaxy ($z \sim 3.5$), Hα would be shifted redward of K-band and would be undetectable from the ground.

We could expect much fainter $K-$band magnitudes of 23–26 for similar ULIG/sub-mm galaxies ($\gtrsim 10^{12}L_{\odot}$) which are unlensed. Therefore, obtaining optical/NIR redshifts for many of the sub-mm galaxies may have to wait for the Next Generation Space Telescope. Alternatively, redshifts could be directly measured from the CO lines themselves with future ground-based instruments, such as the Atacama Large Millimeter Array (ALMA), operating at mm-wavelengths (Blain et al. 2000). Sensitive interferometric observations at sub-mm/mm-wavelengths with the next generation of instruments will be crucial for our understanding of these dust-obscured systems.

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